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A model of sustainable production: ecological and economic benefits of high-gloss UV-coating in offset printing without a relevant loss in gloss quality

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Abstract

This paper presents a guideline for enterprises to realize sustainable production in compliance to economic interests. A special perspective on the product quality that is perceptually noticeable, or required for customer satisfaction, enables to reach economic benefits not conflicting in respect with the principles of sustainability. Therefore, the model of sustainable production was exemplarily demonstrated by the glossiness of cardboard packaging. The investigation was mainly concentrated on the gloss measurement and perception aiming to define a threshold of perceptual gloss that gives information about the product quality required. Gloss has been a part of research work for decades. However, there are no researchers known who were able to quantify a threshold that inform about noticeable gloss differences. Furthermore, the measurement technology of gloss is much more complex than expected. The specular gloss is still the main important feature, and is broadly the essential measure in practical application. However, further gloss types are implemented in so-called goniophotometric instruments. In this paper, the currently available knowledge in gloss perception and measurement is used to generate a measure of perceptible gloss differences. Influencing factors affecting the environmental performance of high-gloss cardboard packages are presented, and suitable methods for measurement are employed. For high-gloss coated cardboard packaging, the volume of the coating roller and the intensity of the UV-curing unit reveal potential for sustainable production under consideration of the threshold of 2.0 Gloss Units that is recommended from a visual test performed. Considering the assumption made for the product example, 0.99 ± 0.65 $g \cdot m^{-2}$ of UV-coating and 6.6 ± 3.8 kWh of energy could be saved. The integration of these scenarios in life cycle assessment (LCA) on coatings will help to assume whether these savings are crucial in the whole product life cycle. This paper gives first impressions.

Keywords: gloss measurement, gloss perception, ecological assessment, cardboard packaging, quality assessment

1. Introduction

Sustainability is one of the most important aims in society. In this context, enterprises are forced to establish sustainable strategies, also in the printing and packaging industry. A general presumption is widely spread in enterprises that sustainable strategies mainly conflict with economic objectives. However, an immediate interplay between sustainable initiatives and business competitiveness could not been found (Clausen, Klein and Konrad, 2003).

The model of sustainable production presents potential for optimisation in the manufacturing process in order to generate ecological and economic benefits. It is strongly related to a threshold of product quality due to fulfil customer satisfaction and to reach the required level of livelihood security. As an example, the coating of cardboard packages was investigated concerning gloss quality, and the consumption of materials and energy. Therefore, experiments were performed employing gloss measurement, visual testing methods, measurement of the coating's weight, and power profiling of the printing machine. In this research study, gloss is the main challenging method of measurement. It is fundamental for this study to quantify the gloss quality and to identify a threshold of gloss perception. All of the following conclusions within the study depend on this gloss level. Gloss has been part of research work for decades but until now several research questions have not been solved.

Applying the proposed model of sustainable production in the packaging industry, ecological and economic potential of the coating process are determined without a lost of gloss quality. Based on this representative example, this study illustrates how sustainable strategies could be organized in enterprises reducing ecological and economic demands without an implication of economic objectives.

2. Literature review

Gloss is one of the main criteria of product quality for carton packages in the printing and packaging industry. An optical feature, such as gloss, can positively affect consumers' decisions at the point-of-sale (Loefgren, 2005; ProCarton, 2006; Seeger, 2009). Thus, printing enterprises should assess and control gloss in the manufacturing process of cardboard packaging. The monitoring reveals potential for optimisation in quality, and additionally, in ecological and economic aspects, e.g. the use of resources and energy.

Important advances in gloss measurement and perception have been made since the 1930s. Initially expected to be a single objectively measureable attribute of surfaces, gloss was found to be more complex (Chadwick and Kentridge, 2015).

The most simple gloss type is called 'specular gloss', and describes the ratio of the portion of light in the reflectance angle to the portion of light in the incidence angle (DIN, 2014). In compliance to this norm, an angle of 20, 60 or 85 degrees is optionally employed depending on the gloss level associated: 'high-gloss', 'medium' and 'low-gloss'. In industrial applications, enterprises mostly consider specular gloss in the gloss measurement, although it was found that gloss is a multi-dimensional feature, as shown in Hunter (1937) and Hunter and Harold (1987). They stated that further gloss types have to be involved in gloss measurement. Goniophotometric instruments normally generate measurements of light reflectance in the specular angle and, as well, in areas nearby. These gloss data are sufficient to cover the gloss types proposed by Hunter and Harold (1987), as can be seen in Figure 1.

Along with the multi-dimensionality, it is not apparent whether physical measures correlate with the perceptual judgement of gloss. Wendt (2009) emphasized that gloss is not only a purely physical attribute but also covers psychological perception and interpretation. The 'perceptual gloss' describes complex interactions between illumination, object, its surface reflectance, and observer (Chadwick and Kentridge, 2015), and remains gloss measurement being demanding.

Prior research has noted that observers are not able to differentiate strictly the effect of the gloss types, and hence, the test persons mainly interpreted the glossiness of samples jointly (Ged et al., 2010; Harrison and Poulter, 1951). However, a multi-dimensional model including gloss types proposed by Hunter does not exist (Wendt, 2009). The magnitude of each gloss type contributing to the gloss perception has not been identified. Chadwick and Kentridge (2015) concluded from their literature review on the perception of gloss that further work is required to create a suitable model. The variability is high in previous research work on perceptual judgement from object to object and from observer to observer. They stated that the full extent of relevant data have to be generated to reach inter-observer agreements in visual judgements and thus to develop a model.

Research work that deals with an in-depth discussion of perceptible gloss differences is not known. Authors mentioned an unspecific differential threshold of 3 GU (Gloss Unit) up to 12 GU, e.g. Helbig and Bosse (1993) and Kettler (2005). Ignell, Kleist and Rigdahl (2010) mentioned perceptible gloss differences for textured

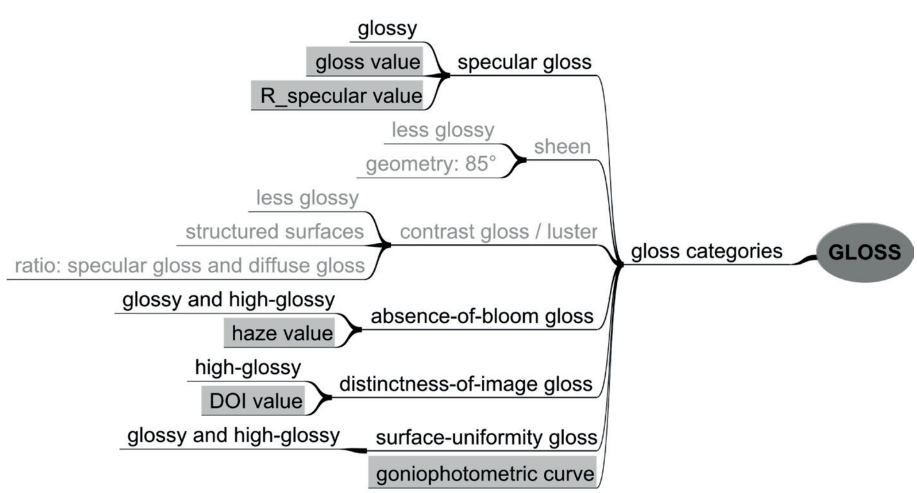


Figure 1: Connection between six gloss types mentioned by Hunter and Harold (1987) and the gloss parameters: gloss (= specular gloss), Rspec (= specular peak), haze (= absence-of-bloom gloss), and DOI (= distinctness-of-image gloss) of the goniophotometric instrument Rhopoint IQ (Rhopoint Instruments Ltd., UK) (cf. Radermacher, Dieckmann and Jung, 2015; Radermacher, 2016)

polymeric specimens of 1 GU to 5 GU, and a lower value of 0.1 GU, measured at 60°. The paper aims to develop sustainable strategies in enterprises in compliance to the product quality required. Therefore, several single aims are addressed in this study: (a) generating gloss measurements with high extent of information, (b) developing a measure of perceptible gloss differences, (c) identifying factors that are able to change, or not to change the glossiness of UV-coated samples, (d) choosing factors that offer ecological and economic potential, and (e) quantifying the potential for optimisation.

3. Methods

This study consists of different analyses. Figure 2 presents how these analyses are connected to each other. A pool of influencing factors that may have ecological and economic potential are analysed in gloss measurements of test samples. The statistical relevant data are assessed under consideration of a threshold of perceptual gloss that is extracted from a visual test. Specific factors out of the pool are chosen that do not affect the gloss quality and moreover, have ecological and economic potential in cases of material and energy consumption to implement sustainable production.

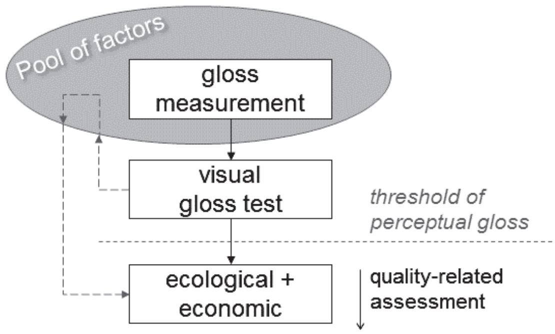


Figure 2: Methods for creating the model of sustainable production including the gloss quality of high-gloss coated cardboard packaging

3.1 Gloss measurement

Seven sets of gloss data (cf. Table 1) were calculated by taking into consideration varying factors in UV-coating that are able to affect resource and energy consumption in the coating process. Each data set was generated out of 150 measurements to achieve higher confidence in the gloss results.

Important factors with ecological and economic potential are associated with the anilox roller of the coating unit, and conditions in the drying and curing unit: (a) screening type, (b) gravure (screening volume, and frequency), (c) power of UV-curing, and (d) existence of IR-drying. The experiment is designed to quantify the effect of each of these influencing factors by varying production conditions in the coating process, as demonstrated in Table 1. For all of these conditions, test samples were created in the printing laboratory. Under consideration of climate-controlled conditions, the test samples were offline UV-coated with transparent varnish on the SM52-4+L-Anicolor-UV offset printing machine with a print run of 8 000 sheets per hour (sph) (Heidelberger Druckmaschinen AG, Heidelberg, Germany). The substrate is a white, double coated duplex board with a grammage of 250 $g \cdot m^{-2}$ (Multicolor Mirabell, MM Karton, Neuss, Germany).

In Radermacher, Dieckmann and Jung (2015), the effect of the underlying colour on gloss measurements of high-gloss UV-coating was statistically significant for the gloss types: specular gloss at 20° for high-gloss samples according to DIN (2014) ‘G20’ and the absence-of-bloom gloss ‘haze’. The colour-related gloss could also be concluded from results in Karlović, Novaković and Novotny (2010). Thus, in favour of robust results in the comparison of gloss data in this study, the colour of the test samples must not vary. Therefore, the patches of the test samples were previously 1 colour printed (black). A preliminary coating test of four different types of UV-varnishes facilitated the choice of coating that reaches the highest gloss quality. The UV varnish is 100 % polymer-based for a radical polymerisation process.

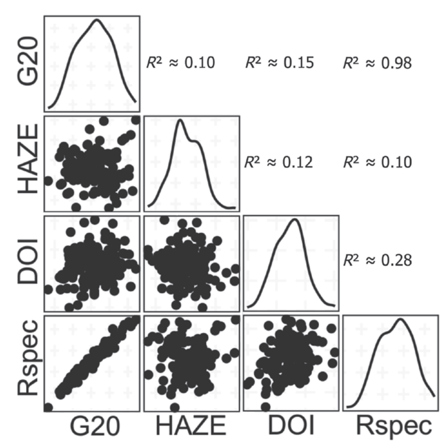


Figure 3: Scatter plot of the gloss parameters, specular gloss at 20° (G20), specular peak (Rspec), absence-of-bloom gloss (haze), and distinctness-of-image gloss (DOI) of data set i = 2, and the belonging Pearson’s correlation coefficients, see Table 1 (cf. Radermacher, 2016)

The gloss measurements were performed by a goniophotometric instrument ‘Rhopoint IQ’ (Rhopoint Instruments Ltd., UK). As shown in the statistical correlation analysis of the output variables in Figure 3,

Table 1: Experimental data sets of test samples UV-coated in a sheet-fed offset printing process (SM52-4+L Anicolor UV; print run of 8 000 sph; background colour: black patches)

DATA		CONDITIONS			
ID i	**n**	**type**	**gravure [cm³ · m⁻²] / [lines · cm⁻¹]**	**UV-dryer [%]**	**IR-dryer**
1	150	strd	13.0 / 100	100	on
2 *)	150	bnd	13.7 / 100	100	on
3	150	bnd	19.0 / 80	100	on
4	150	bnd	25.5 / 60	100	on
5	150	bnd	13.7 / 100	80	on
6	150	bnd	13.7 / 100	60	on
7	150	bnd	13.7 / 100	100	off
		(a)	(b)	(c)	(d)

Abbreviations: 'strd' = standard roller with conventional cell screening; 'bnd' = roller with three different volumes and hexagonal screening;
*) In order to fulfil the requirements of statistical analysis, as summarized in Sachs (2004), e.g. independent testing situations for the investigation of different research questions, the random sampling of this data set was repeated.

the parameters G20, haze and distinctness-of-image gloss 'DOI' are not related, and are mutually supportive to define gloss. Contrarily, the Pearson's correlation coefficient of the specular peak 'Rspec' and G20 is extremely high ($r = 0.98 \pm 0.01$ and $t(148) = 62.5$, $p < 0.001$). However, Rspec may have informative potential if G20 does not represent differences between data sets that are visually perceptible. Thus, the gloss measuring was focused on parameters like specular gloss G20, the specular peak Rspec, the absence-of-bloom gloss haze and the distinctness-of-image gloss DOI. The gloss types were estimated separately to overcome the lack of a multi-dimensional model. For each parameter, the mean value $\bar{x}$, the expected value μ with a 95 % confidence interval, and the mean difference $\Delta\mu_{i,j}$ of data set i to j were statistically calculated by the general two-sample t-testing method, described in Faraway (2006). The open-source software R was utilized for statistical computation.

3.2 Visual judgement

The statistical analysis can solely illuminate statistically significant results. In order to infer the practical relevance, a visual test of transparently high-gloss laminated paper-white samples by 20 test persons was carried out. The test cabine was prepared in agreement to ASTM 4449 (ASTM, 2008), Obein, Knoblauch and Vienot (2004) and Leloup et al. (2011). The testing procedure was constructed aiming to imitate precisely the measuring geometry of gloss instruments. In particular, an illumination and reflectance angle of 20° and the proposed distance between sample and test person for each of the gloss types were strictly kept. The samples were judged binocular in order to enhance the ability of test persons to identify gloss differences (Obein, Knoblauch and Vienot, 2004). The visual test was separated into three parts: a test of visual capability in compliance to DIN 8596 (DIN, 2009), a test of gloss knowledge and the main visual test by pairwise comparison including a consistency test. The successful answering in the first two tests qualify the test persons to participate in the key test of visual judgement.

3.3 Ecological and economic assessment

Depending on the conclusions from the analyses described in section 3.1 and 3.2, ecological and economic potentials were quantified in this study, especially for (a) the weight of coating and (b) the power profile of the printing machine.
(a) The weight of the dry coating layer was measured gravimetrically applying the scale Mettler AE 200 (Mettler-Toledo GmbH, Giessen, Germany) with a measuring uncertainty of ± 0.1 mg. Sixty samples in dimensions of 50 mm × 70 mm, were randomly extracted from the mass of samples, and were measured in three procedures. The data set of 180 measurements for each instance were assessed in statistical comparison of $\Delta\mu_{i,j}$ and scaled up to one square metre. The determination of the thickness by scanning the surface mechanically with the Dektak 150 surface profiler failed in a previous test procedure because the high roughness of the coated prints prevents the calibration and levelling of the system. Optical systems will complicate measurements, as well, because of transparent properties of the coating. Thus, the gravimetric measurement seems to be the most suitable method for quantifying the weight of the UV-coating.

(b) A power profile of the printing machine was documented in two test productions using the power quality analyser LEM 3Q (LEM HEME, Skelmersdale, UK). The instrument records 1440 intervals as the maximum in reference to the production time. The energy demand of the coating process was calculated for the reference-scenario 'coating of 5000 cardboard packages (size: 155 mm × 90 mm × 45 mm)' considering the production conditions described above. The real power values of each of the printing status are averaged and related to the production time assumed for the reference-scenario.

4. Results

In this chapter, the results extracted from several analyses that are introduced in chapter 3, are summarized, connected to each other and discussed in order to answer the overall research questions.

4.1 Statistical confirmation of gloss differences

The glossiness of test prints of Table 1 are statistically computed and shown in Table 2. The screening type of the anilox roller of the coating unit ($\Delta\mu_{1,2}$) and the additional IR-drying unit ($\Delta\mu_{2,7}$) influence the gloss of the test prints more effectively than the gravure of the anilox roller ($\Delta\mu_{2,3}$) and the power of UV-curing ($\Delta\mu_{2,6}$) as specified in this test procedure. The values of distinctness-of-image gloss (μ_{DOI}) seems not to be affected notably by any of the coating conditions investigated. In three out of four factors, the results of the t-tests are not even statistically significant. As known from section 3.1, the specular peak Rspec is just to confirm G20 differences. Thus, the analysis in the following is focussed on the values of specular gloss (μ_{G20}) and absence-of-bloom gloss (μ_{haze}).

The hexagonal raster ('bnd') of the ceramic anilox roller (Zecher GmbH, Paderborn, Germany) is expected to transport the varnish out of the chambered doctor blade system reaching a highly smooth surface of the coating in contrast to a ceramic anilox roller with conventional cell raster ('strd'). This statement is proved by μ_{G20} and μ_{haze}: $\mu_{G20,2}$ is 1.7 ± 0.5 GU higher than $\mu_{G20,1}$, and $\mu_{haze,2}$ is 1.0 ± 0.3 HU (Haze Unit) lower than $\mu_{haze,1}$ (cf. Table 2a).

Table 2: Effect of the influencing factors (a) screening type, (b) gravure (screening volume, and frequency), (c) power of UV-curing, and (d) additional IR-drying on the gloss values μ_{G20}, μ_{haze}, μ_{DOI}, and μ_{Rspec}

DATA		GLOSS VALUES			
i	***n***	**μ_{G20} [GU]**	**μ_{haze} [GU]**	**μ_{DOI} [GU]**	**μ_{Rspec} [GU]**
(a) screening type:					
1	150	37.9 ± 0.4	29.4 ± 0.2	4.5 ± 0.2	5.5 ± 0.1
2	150	39.6 ± 0.4	28.3 ± 0.2	4.9 ± 0.2	5.7 ± 0.1
$\Delta\mu_{1,2}$		**1.7 ± 0.5**	**1.0 ± 0.3**	**0.4 ± 0.3**	**0.3 ± 0.1**
(b) gravure (screening volume, and frequency):					
2	150	41.9 ± 0.4	27.7 ± 0.2	5.1 ± 0.2	6.1 ± 0.1
3	150	42.7 ± 0.3	27.8 ± 0.2	5.3 ± 0.3	6.3 ± 0.1
4	150	37.6 ± 0.3	32.4 ± 0.2	4.6 ± 0.2	5.4 ± 0.1
$\Delta\mu_{2,3}$		**0.9 ± 0.5**	**0.1 ± 0.3 *)**	**0.1 ± 0.3 *)**	**0.1 ± 0.1**
(c) power of UV-curing:					
2	150	39.6 ± 0.4	28.3 ± 0.2	4.9 ± 0.2	5.7 ± 0.1
5	150	39.1 ± 0.4	29.2 ± 0.2	4.8 ± 0.2	5.7 ± 0.1
6	150	39.0 ± 0.4	28.8 ± 0.2	4.8 ± 0.2	5.6 ± 0.1
$\Delta\mu_{2,6}$		**0.6 ± 0.5**	**0.5 ± 0.3**	**0.1 ± 0.4 *)**	**0.1 ± 0.1**
(d) additional IR-drying:					
2	150	40.2 ± 0.3	28.4 ± 0.2	4.9 ± 0.2	5.8 ± 0.1
7	150	38.4 ± 0.5	30.0 ± 0.3	4.8 ± 0.2	5.6 ± 0.1
$\Delta\mu_{2,7}$		**1.8 ± 0.6**	**1.5 ± 0.4**	**0.1 ± 0.2 *)**	**0.2 ± 0.1**
*) No statistically significant results in the two-sample t-testing					

The increase of volume from 13.7 $cm^3 \cdot m^{-2}$ and a frequency of 100 $lines \cdot cm^{-1}$ ('B1') to 19.0 $cm^3 \cdot m^{-2}$ and 80 $lines \cdot cm^{-1}$ ('B2') rises the gloss value G20 slightly by 0.9 ± 0.5 GU. The effect on haze is statistically not significant (cf. Table 2b). A volume of 25.5 $cm^3 \cdot m^{-2}$ and a frequency of 60 $lines \cdot cm^{-1}$ ('B3') leads to a strong reduction of the glossiness of the samples.

The status of curing in the UV-coating process varies with the print run, and also with the intensity of the UV-lamps of the curing unit. Thus, it is suspected that the reduction of the UV-power in the curing unit has an impact on the coating surface. However, the reduction from 100 % to 60 % is actually small. A little decrease of $\Delta\mu_{G20,2,6}$ by 0.6 ± 0.5 GU and a small increase of $\Delta\mu_{haze,2,6}$ by 0.5 ± 0.3 HU are recognized (cf. Table 2c).

An IR-drying unit (rated output: 23.1 kW at 400 V) is additionally installed in the printing machine. Generally, IR-dryers are needed for hardening inks and coatings that contain physically drying ingredients. The UV-varnish used in this test production is a 100 %-polymeric material. However, as confirmed by further tests in the laboratory, the IR-drying process supports the curing process of coatings, and the creation of mostly smooth surfaces. The gloss values grow by $\Delta\mu_{G20,7,2}$ = 1.8 ± 0.6 GU and decline by $\Delta\mu_{haze,7,2}$ = 1.5 ± 0.4 HU (cf. Table 2d).

4.2 Visual judgement of gloss differences

The statistical results in Table 2 were verified including conclusions from the visual judgement. This visual judgement aims to describe gloss differences in a comparative perceptual test by qualitative means. Twenty test persons (8 female, 12 male) were admitted to participate in the main test. The objects passed the eye test of DIN 8596 (DIN, 2009) and the pre-test demonstrating that they had understood the testing procedure.

Each test pair was judged, in a proceeding of sample i to sample j and vice versa. The consistency of judgement was then calculated in percent out of six test pairs. The overall consistency c is high for all of the three gloss types: c_{G20} = 0.75, c_{haze} = 0.80 and c_{DOI} = 0.85. Thus, the answering of the test persons is assumed to be self-consistent.

For specular gloss G20, a positive trend was derived from the pairwise comparison: The higher the mean difference $\Delta\mu_{G20}$, the higher the rate of correct answers of the test persons (cf. Figure 4). However, the determination coefficient R^2 of 0.2 is low. The trend was not even noticeable for haze and DOI. Test persons disclosed their difficulties to differentiate these gloss types from G20, despite a declaration of the gloss types at the beginning of the visual test.

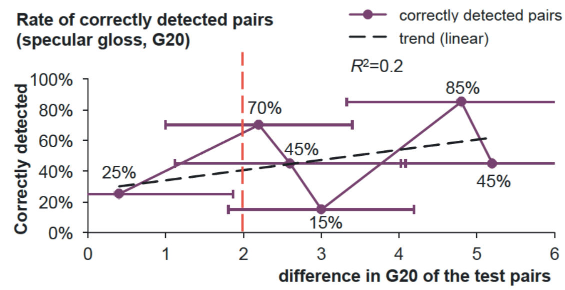


Figure 4: Rates of correctly detected test pairs of high-gloss transparently laminated samples – a result of the visual judgement of 20 test persons (cf. Radermacher, 2016)

For this reason, a measure of the practical relevance was focussed on specular gloss. The threshold for the measured gloss differences was set to 2.0 GU because 70 % of the test persons were still able to detected the gloss difference of the test pairs at a gloss level of 2.2 GU correctly.

Considering a threshold of gloss perception of 2.0 GU, the volume of the anilox roller and the power of the UV-curing unit do not affect the glossiness of cardboard packages perceptibly, and hence offers potential for sustainable production. The effect is quantified in section 4.3 and 4.4.

4.3 Ecological and economic effect of the anilox roller

A change of the anilox roller from 'B2' to 'B1' have no notable influence on the glossiness of the specimens. The gloss difference between $\mu_{G20,B1}$ = 41.9 ± 0.4 GU and $\mu_{G20,B2}$ = 42.7 ± 0.3 GU is lower than the threshold of 2.0 GU; instead, the reduction of the volume may show ecological and economic potential.

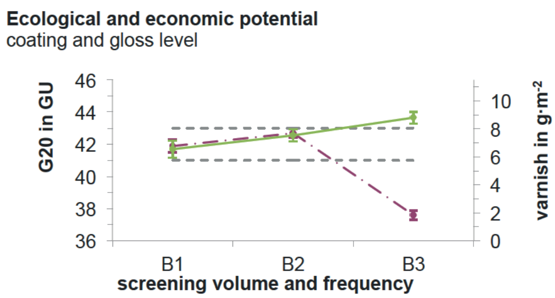
The dry coating layer was gravimetrically measured, and comparatively analysed regarding to the weight of uncoated test samples. The statistical results are shown in Table 3.

The data confirm that the volume directly correlate with the amount of varnish actually transferred to the substrate. This means that the parameters of the anilox roller (volume, and frequency) can directly improve ecological objectives, e.g. the material consumption of the varnish.

Figure 5 illustrates the variation of the coating amount and the effect on the glossiness of the specimens. The quantity of varnish expressed as a specific weight tends to increase slightly with higher volume of the coating roller. The gravimetric measurements for the coated test prints are presented in 'B1' $\mu_{g,B1}$ = 6.5 ± 0.6 $g \cdot m^{-2}$ and in 'B2' $\mu_{g,B2}$ = 7.5 ± 0.5 $g \cdot m^{-2}$. As a conclusion, the reduction of material consumption in the manufacturing process can be quantified as 0.99 ± 0.65 $g \cdot m^{-2}$.

Table 3: Mean $\bar{x}$, deviation σ and expected value μ with a confidence interval of 95 % of gravimetric measurements of uncoated and coated test samples with a size of 50 mm × 70 mm scaled up to 1 m²

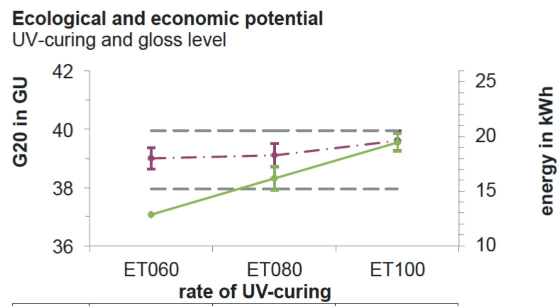
	n	$\bar{x}$ [$g \cdot m^{-2}$]	σ [$g \cdot m^{-2}$]	μ [$g \cdot m^{-2}$]
Uncoated paper, 250 $g \cdot m^{-2}$	180	250.44	2.77	250.44 ± 0.41
Coated paper, B1	180	256.98	3.30	256.98 ± 0.48
Coated paper, B2	180	257.97	3.26	257.97 ± 0.48
Coated paper, B3	180	259.23	3.00	259.23 ± 0.44



G20	41.9 ± 0.4	42.7 ± 0.3	37.6 ± 0.3
varnish	6.5 ± 0.6	7.5 ± 0.5	8.8 ± 0.4

G20 in GU
threshold of gloss
coating, dry

Figure 5: Ecological-economic analysis of UV-coated prints: Variation of gravure (screening volume, and frequency) (B1, B2, and B3) considering a threshold of 2.0 GU



G20	39.0 ± 0.4	39.1 ± 0.4	39.6 ± 0.4
power	12.9	16.2 ± 1.1	19.5 ± 0.8

G20 in GU
threshold of gloss
energy in kWh

Figure 6: Ecological-economic analysis of UV-coated prints: Variation of the energy in the UV-curing process (100 % curing, dimming to 80 % and 60 %) considering a threshold of 2.0 GU

4.4 Ecological and economic effect of the UV-curing power

The power profile of the printing machine clarifies the real power in watt for different status of the printing machine. As illustrated in Table 4, an energy demand of 19.5 ± 0.8 kWh (with 100 % curing) was calculated. In the case of 80 % power of the curing unit, the energy consumption declines to 16.1 ± 1.1 kWh. The power profile of the printing machine indicates that the dimming of the UV-curing lamps effectively reduces the energy consumption.

Table 4: Power consumption values of the printing machine 'SM52-4+L Anicolor UV' at coating 5 000 cardboard packages (plus 100 pcs. of coated paper waste) to different production status (reference-scenario)

Status	Duration [min]	Real power [kW]
Starting	5	14.25 ± 1.4
General preparation of the machine	5	8.86 ± 1.1
Pumping up varnish *)	8	11.48 ± 1.2
Driving down of coating unit	2	18.35 ± 1.5
Preparing UV dryer	1	21.95 ± 2.9
Driving of minimum limit of varnish	5	29.87 ± 1.7
Print run (100 % curing)	38	31.07 ± 2.2
Driving up coating unit	2	32.48 ± 4.3
Pumping down varnish	3	17.70 ± 0.4
Cleaning of coating unit *)	5	18.21 ± 0.5
*) Cleaning and setting of the coating unit is allocated to the daily average production in two-shift operation with an average print run of 10 000 sph (~ 3 %)		

The ecological and economic potential of the UV-curing power in the coating process is presented in Figure 6.

The effect on the gloss quality and the energy in kWh are visualized comparatively. The steady decrease of the power of UV-curing lamps from 100 % to 60 % does not influence the glossiness of the prints negatively considering the threshold of perceptible gloss differences determined in section 4.2. Assuming a linear correlation between dimming rate and energy demand, the reduction of the curing intensity to 60 % leads to a potential for energy reduction of 6.6 ± 3.8 kWh.

5. Discussion and conclusion

This study presents a special perspective on sustainable production. The model enables to discuss ecological benefits including a threshold of quality differences. The consumption of materials and energy that will not affect the product quality could be seen as a kind of wastage, see also Pommer et al. (2003). For the example of gloss quality, addressed in this study, two factors were found out to give ecological and economic benefits: The intensity of UV-curing and the amount of UV-varnish. This conclusion was based on results of goniophotometric gloss measurements and visual testing. A threshold of 2.0 GU was defined to be visually noticeable. Additional analyses were utilized to quantify the ecological and economic advantages.

In the gravimetric measurement of the coating, it was confirmed that an increase of the volume of the anilox roller raises in fact the coating layer thickness of the test prints. Generally, the measuring method has a high deviation. However, it was stated that mechanical and optical systems for profiling coating surfaces, which are available in the laboratory, would not be applicable to this request. A reduction of about 0.99 ± 0.65 $g \cdot m^{-2}$ was concluded to have ecological and economic potential not affecting the gloss quality of the specimens.

The power profile of the printing machine was recorded to construct the energy demand of the coating process in a modular way. This proceeding enables to develop different scenarios based on specific assumption in the coating process. This power values illuminates that the IR-drying unit has an essential effect on the glossiness of the test samples although the UV-varnish does not contain physically drying ingredients but exclusively 100 % polymers. It could be concluded that the built-up of heat at the coatings of the samples positively influences the UV-curing process and reaches better pre-conditions to create smooth coating surfaces. The intensity of the UV-curing was not found to be relevant regarding to the level of gloss quality. The dimming from 100 % to 60 % does not cause perceptible gloss differences, but can reduce the energy demand by about 6.6 ± 3.8 kWh. This comparative analysis of ecological and economic aspects is concentrated on the energy demand. It was not stated in this study whether the potential of the migration of monomers and photo-initiators will be negatively implicated in this case. For this study, the equipment was not available to include this information. It is recommended to examine if the energy reduction does not influence the quality of the curing and increase the risk for human health. Research work has been conducted to develop effective measures for the curing degree of UV-coatings and UV-inks. Until now, these methods for determination of the curing have not been established in printing companies, and hence, the degree of curing cannot be controlled during printing. That is why the dimming of the UV-dryer is not a usual behaviour in practical application to be sure that the coating is completely polymerized. However, in general, this is representative to demonstrate the model of sustainable production, and to identify different influencing factors with high effect on the glossiness.

The analysis of these factors is of major importance for the model of sustainable production. This kind of effect analysis is the basis of the model, and hence, requires high accuracy in the testing procedures, as standard conditions in the laboratory (e.g. climate) and constant testing set-up (e.g. machine, material), for all of the test variations to create reliable results. These pre-conditions were considered in this study so that systematic errors in the conclusions could mainly be eliminated. The gloss measurement was focused on the gloss types, specular gloss ‘G20’, absence-of-bloom gloss ‘haze’ and distinctness-of-image gloss ‘DOI’. The study presents that these gloss types are not correlated and can be included in a multi-dimensional model. Additionally, the specular peak ‘Rspec’ was included although this gloss type is strongly related to specular gloss. The manufacturer of the gloss instrument recommends to use this measure for the specification of perceptual gloss that is not detected by the specular gloss type. These four gloss types were calculated separately in compliance to Billmeyer and O’Donnell (1987) because a standard model was not obtained to describe gloss perception in a multi-dimensional way. Goniophotometric gloss values were generated using statistical methods. The mean differences were statistically confirmed with a confidence of 95 %, as a general requirement in statisq tical computation (Sachs, 2004; Sachs and Hedderich, 2009). Although Rspec was expected to give informai tive results to G20, this gloss type was not found to be relevant in this study. The distinctness-of-image gloss DOI did not generate consistent information, too; DOI seems not to be sensitive in any of the adjustments in the coating process investigated in this study. A statistical relevance was not realized in the main of the data sets. Thus, it may be concluded that distinctness-of-image gloss is a measure of different application methods, and does not differentiate modifications of production conditions in one of the techniques, as coating in a printing machine. Nevertheless, specular gloss and haze are two gloss types that create important information about the coating in this study.

In order to estimate the practical relevance of the gloss differences, a visual test was conducted. The visual judgement did not present robust results. A positive trend of gloss differences measured and judged was only visible for specular gloss demonstrating a high deviation. This seems to confirm the statement of Chadwick and Kentridge (2015) that further work on relevant data is required to generate inter-observer agreements in visual judgement. However, the threshold of perceptible gloss differences was defined reasonably and quantify suggestions of Helbig and Bosse (1993), Kettler (2005) and Ignell, Kleist and Rigdahl (2010) more precisely.

This paper presents how principles of sustainable production could effectively be used in the printing and packaging industry. In accordance to the proposed model, decision-making is primarily based on a comparative level of perceptual product quality. In a wider context, the ecological benefits could be discussed not from a comparative but from an absolute perspective. This means, the level of quality that is actually required could be included in the model of sustainable production. This kind of quality level considers a threshold that is needed to fulfil customer satisfaction. In the case of carton packages, this threshold could be defined by research work on consumers' behaviour.

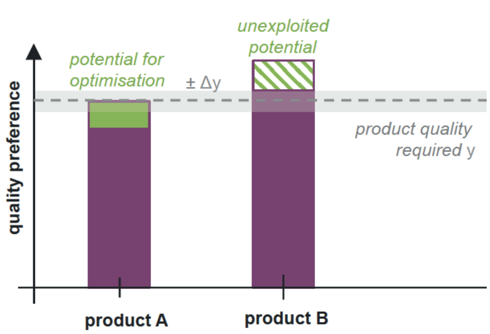


Figure 7: Potential of sustainable production in product comparison under consideration of the product quality required: product A has potential for optimisation; product B creates unexploited potential and hence shows potential for reduction

As shown in the scheme in Figure 7, the absolute value for product quality $y \pm \Delta y$ may give rich information about the potential for process optimisation in product A, and the stage of wastage in product B.

This model of sustainable production reaches a high level of practical applicability, and is additionally flexible to be adapted to several industries. Ecological and economic objectives are essential in producing industries. However, this model does not conflict with the principles of sustainability: Ecological and economic aspects are forbidden to be balanced in the sustainable discussion. Instead, the model considers a minimum limit of product quality required to secure the livelihood of enterprises.

The example of coated cardboard packages presents absolute values of resource consumption. This potential is related to assumptions made in the test specimens and in the set-up of the coating process. There is no information about the overall potential in the product life-cycle and its emissions to the environment from the perspective of the final product. The life-cycle assessment (LCA) is a method that estimates the environmental impact from the material extraction to the end-of-life phase. The LCA method has been part of research work for decades. The inclusion of the stages of production was found to be essential for strategic decision-making of enterprises; whereby, LCAs are known to be particularly complex.

For the specific product in this study, Radermacher (2016) reports LCA results for this kind of coating under consideration of the different production conditions in this study. This publication reports that the volume of the anilox roller affects the ecological benefit more remarkably than the dimming rate of the UV-curing unit does. Depending on the specific impact category, the reduction of the varnish improves the overall impact by 15.0 ± 12.9 % to 24.4 ± 14.8 %. For the energy con4 sumption in the coating process, the reduction is just by 0.4 ± 0.1 % to 6.1 ± 2.6 % of the whole product life cycle.

These results give first impressions about the magnitude of the environmental impact that the coating might have. Additionally, it points out one problem of the LCA methodology: the uncertainty of data. The deviation in the impact factors assessed is caused, for example, by the mass of information included, the scope of data, its adaption and the assumptions in the calculation. This might imply that LCA is not appropriate although it is the most informative method including potential impacts based on scientific research and going further than the 'less is better' argument. Because of the extensive perspective on the whole product life-cycle, this approach detects displacements of burdens to other stages of the life-cycle (Fava, 2002) and could prevent mistakes in decision-making. Especially the last-mentioned fact is important for enterprises in the context of sustainable production and should be forced in future strategic development. However, further research work on the LCA is required to include this kind of environmental assessment more consistently in businesses.

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